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TITLE: Generation of Surfaces with Smooth Highlight Lines

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TITLE: International Conference on Curves and Surfaces [4th], Saint-Malo, France, 1-7 July 1999. Proceedings, Volume 1. Curve and Surface Design

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Generation of Surfaces with Smooth Highlight Lines

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Abstract. This paper proposes a method which generates smooth surfaces from four boundary curves. A criterion is introduced to represent smoothness of highlight lines which are an approximation of reflection lines and are sensitive to the surface irregularity. The criterion is the square of projected curvature of highlight lines per unit length. To obtain the surfaces which satisfy the criterion, the evolutes of their parametric lines which influence highlight lines are determined to change smoothly. The evolutes are represented with two segments of second-degree rational Bézier curves, whose parameters are determined to minimize the criterion. The method is extended to determine a surface when a highlight line is given by a designer. Some examples of boundary curves with various patterns of curvature variation are shown to generate smooth surfaces.

§1. Introduction

In the design of aesthetic shapes like automotive bodies, curvature variation of surfaces is very important. Designers determine shapes according to their great concern for the reflected images of the surroundings, shade lines, and highlight lines. Since reflection and shading are affected by changes of surface normal, the curvature distribution of the surface should be smooth and formed as designers want.

Spline interpolation, fairing and lofting methods [3,8] which are widely employed in industrial applications cannot assure smooth distribution of curvature of a surface, although they generate surfaces which pass through the given points and satisfy second degree continuity. On the other hand, methods [4,10] which simulate the minimization of the elastic energy for a thin plate can generate smooth surfaces, but cannot always obtain the shape which designers want for the given boundary conditions.

Hence we have proposed a surface generation method [7] which directly determines curvature distribution of a surface from four boundary curves by smoothly interpolating the locus of an *evolute* of a generatrix of a surface. In this paper, we extend the method to determine a shape which has smooth highlight lines directly according to the criterion introduced.

Curve and Surface Design: Saint-Malo 1999
Pierre-Jean Laurent, Paul Sablonnière, and Larry L. Schumaker (eds.), pp. 145–152.

ISBN 0-8265-1356-5.

§2. Highlight Lines and their Criterion

Highlight lines are images (reflection lines) on surfaces of a product or its clay model for parallel lines such as fluorescent lamps on a ceiling, and they are used for the evaluation of surfaces in the automotive industry. If they are not as smooth as designers want, the surface of the clay model is modified until the shape becomes satisfactory.

To evaluate and modify these images in the computer using a CAD system, several methods were proposed. Klass [9] tried to correct local irregularities of a surface using reflection lines. Chen and Beier [1,2] introduced an equation of approximated highlight lines for the real time evaluation of a surface, and applied it to modification of NURBS surfaces. The equation represents normal projection of parallel lines to surfaces. On the other hand, Higashi et al. [5,6] introduced an equation of pseudo-highlight lines which are *silhouette lines* of a surface for incident directions. These highlight lines have been used in a practical CAD system in the automotive industry [5], because they are sensitive to surface irregularities and they had been checked manually on drawings.

Let an incident direction, a surface, and its normal at parameter (u, v) be $\boldsymbol{L}$, $\boldsymbol{S}(u, v)$ and $\boldsymbol{n}(u, v)$. The equation of a silhouette line is

$$\boldsymbol{n}(u, v) \cdot \boldsymbol{L} = 0. \tag{1}$$

If the incident direction is rotated around an axis, we obtain a group of silhouette lines and call them a silhouette pattern.

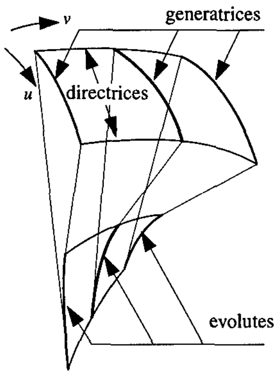
We introduce a criterion H of smooth highlight lines, that is a silhouette pattern, in order to automatically generate a surface which designers want. Let the projected curvature of a silhouette line be $\kappa_i(s)$. Here, suffix i corresponds to highlight line i, s is a parameter of an arclength, and the number of highlight lines is n. We denote the length of each line by s_i. Then we get

$$H = \sum_{i=1}^{n} \int_0^{s_i} \kappa_i^2(s) ds / \sum_{i=1}^{n} s_i. \tag{2}$$

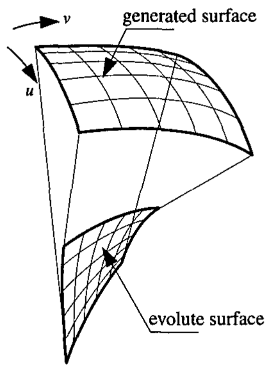
§3. Concept of Surface Generation Based on Evolute

A surface is generated by moving a generatrix along two directrices. When the shape of the generatrix is changed with movement, the interpolation of the movement is not simple. Blending of boundary curves or interpolation of the boundary conditions does not necessarily create a good curvature distribution of the surface.

A generatrix should be moved so that the curvature distribution becomes smooth and satisfies the highlight line criterion described in the previous section. The curvature distribution of the surface is represented as a surface, by making the locus of the evolute of the generatrix. We call the surface generated from the locus an evolute surface. Fig. 1(a) shows an object surface



(a) Generatrix and evolute



(b) Evolute surface and generated surface

Fig. 1. Generatrix and evolute surface.

and its generatrices along with the corresponding evolutes. If the generatrix is a space curve, its evolute cannot be determined uniquely. We define the evolute to be related to the surface property by fixing the freedom around the tangential direction [7]. Let the given curve, the curvature radius and torsion be $\boldsymbol{R}(s)$, $\rho(s)$ and $\tau(s)$, and let $\boldsymbol{n}(s)$ and $\boldsymbol{b}(s)$ denote normal and binormal vectors. They are represented as functions of arclength s. Then the equation of the evolute is

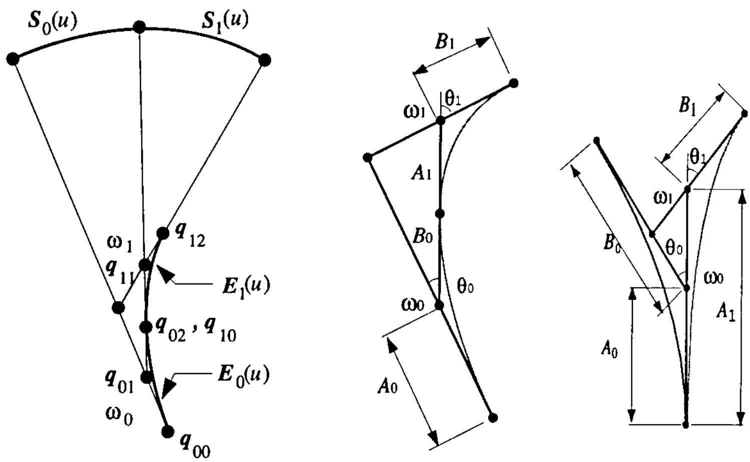
$$\boldsymbol{r}(s) = \boldsymbol{R}(s) + \rho(s)\{\boldsymbol{n}(s) + \tan(-\int \tau(s)ds + \Phi)\boldsymbol{b}(s)\}. \tag{3}$$

We determine the arbitrary constant Φ so that the starting point of the evolute is located at the direction of the surface normal, defined by the outer product of the tangents of the generatrix and the directrix.

Since an evolute is a curve of the curvature center of a generatrix, the quality of the surface is satisfactory if its evolute surface is smooth. Hence we determine the evolute surface first as a smooth surface, and then we align it according to the constraints of the evolute such that the difference of the curvature radii at the end points is equal to the length of the evolute and the tangent directions at the end points of the evolute are the same with those of the normal vectors of the involute. We note that a generatrix corresponds to a v-constant parametric line of the surface, and is represented by parameter u. Let the generated surface (involute), the evolute surface and the curvature radius at the starting point be $\boldsymbol{S}(u,v), \boldsymbol{E}(u,v)$ and $\rho(v)$. Then we get the equation of the object surface:

$$\boldsymbol{S}(u,v) = \boldsymbol{E}(u,v) + \{\rho(v) - \int_0^u |\boldsymbol{E}_u(u,v)|du\}\frac{\boldsymbol{E}_u(u,v)}{|\boldsymbol{E}_u(u,v)|}. \tag{4}$$

Here, the curvature radius $\rho(v)$ is determined by aligning the evolute to the directrices, and suffix u denotes partial differentiation. Fig. 1(b) shows an evolute surface and a generated surface satisfying the constraints.



(a) Control points of evolute (b) Shape parameters

Fig. 2. Control points and shape parameters of evolute.

§4. Surface Generation Satisfying Highlight Line Criterion

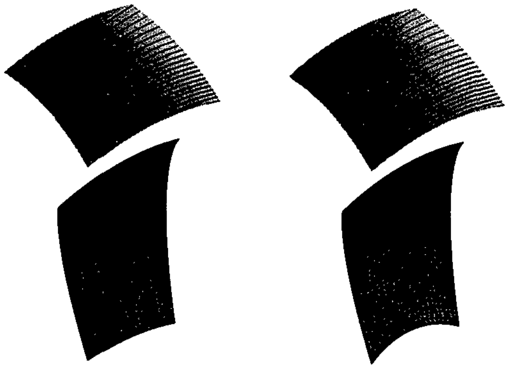
We generate a surface with smooth highlight lines as well as smooth curvature distribution. We approximate the evolute of the generatrix by second-degree rational Bézier curves because they are conics and have smooth curvature distribution. Then, we interpolate an evolute surface smoothly from the evolutes of two boundary curves. If we interpolate the shapes of the evolutes linearly, the surface becomes smooth, but the highlight lines do not necessarily satisfy designers. So, we interpolate the change of the shape of the evolute using a polynomial function.

We approximate an evolute with two segments of Bézier curves as shown in Fig. 2(a). By using two segments, we can represent all the patterns of curvature distribution of a simple curve. The patterns are divided into monotone (increasing or decreasing) and not monotone (with maximum or minimum in the middle). When a curve is not monotone in curvature, its evolute has a cusp point in the middle. Fig. 2(b) shows examples of evolutes and their Bézier polygons for different curvature patterns. The left figure has a monotone curvature distribution, and the right figure has a cusp point at the maximum curvature radius. We connect two segments at the junction point with tangential continuity. Control points $\mathbf{q}_{01}, \mathbf{q}_{02}(\mathbf{q}_{10})$, and $\mathbf{q}_{11}$ are collinear.

Interpolating control points $\mathbf{q}_{i0}, \mathbf{q}_{i1}, \mathbf{q}_{i2}$, and weight ω_i along v direction, we get an evolute surface

$$\mathbf{E}_i(u,v) = \frac{B_0^2(u)\mathbf{q}_{i0}(v) + B_1^2(u)\omega_i(v)\mathbf{q}_{i1}(v) + B_2^2(u)\mathbf{q}_{i2}(v)}{B_0^2(u) + B_1^2(u)\omega_i(v) + B_2^2(u)}. \tag{5}$$

Here, the index i represents the i-th segment, and $B_j^2(u)$ is a Bernstein polynomial.



(a) (b)

Fig. 3. Example 1 of smooth highlight lines. (a) linear interpolation: $H = 0.128 \times 10^{-3}$, (b) minimum H: $H = 0.055 \times 10^{-3}$.

Since we interpolate the shape of the evolute instead of the positions of control points, the number of its independent parameters becomes eight as shown in Fig. 2(b). They are the lengths of edges (A_i, B_i), the included angles θ_i between edges, and the weights ω_i, $i = 1, 2$. Using the shape parameters, we align the control polygons on the directrices. Then we get the functions of control points in (5).

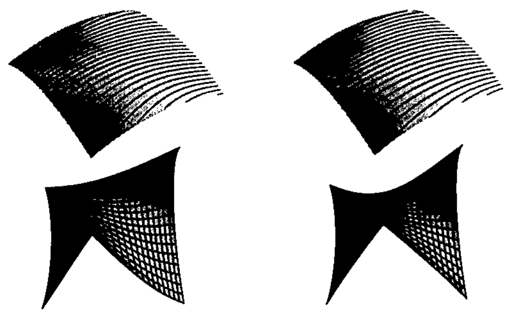
We interpolate these shape parameters smoothly with a second-degree polynomial. Let the set of the parameters be λ. Then we get

$$\lambda(v) = (1-v)^2\lambda(0) + 2v(1-v)\lambda_c + v^2\lambda(1). \tag{6}$$

λ_c is a control variable for each shape parameter. We determine these control variables to obtain a surface with smooth highlight lines by minimizing eq. (2). Starting from the values of λ for the linear interpolation, we search the values for the minimum criterion by changing them so as to decrease H step by step.

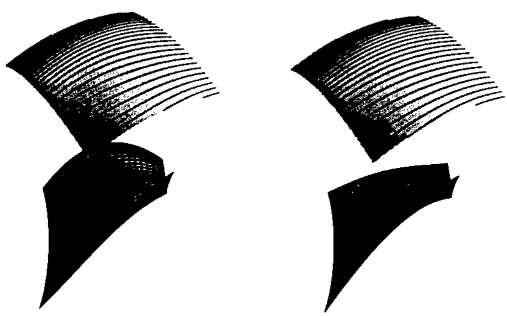
When a given boundary is a space curve, we have to approximate its evolute with third-degree Bézier curves for representing its torsion. In this paper, we only treat planar evolutes, but we can extend the method to the cases of space curves using the algorithm given in [7].

We show some examples of surfaces generated from four boundary curves with different types of curvature distribution. In Fig. 3, both boundary curves have monotonic curvature, but in Fig. 4, they have opposite curvature changes. On the other hand in Fig. 5 one boundary curve has a maximum curvature radius in the middle. Each figure shows an evolute surface and the generated surface with a silhouette pattern on the surface. Figures (a), (c) and (e) are the results of linear interpolation of the shape parameters, while the parameters are determined to get the minimum highlight line criterion in figures (b), (d) and (f). All the surfaces are smoothly generated, but from the point of



(c) (d)

Fig. 4. Example 2 of smooth highlight lines. (c) linear interpolation: $H = 11.24 \times 10^{-3}$, (d) minimum H: $H = 0.139 \times 10^{-3}$.



(e) (f)

Fig. 5. Example 3 of smooth highlight lines. (e) linear interpolation: $H = 0.450 \times 10^{-3}$, (f) minimum H: $H = 0.067 \times 10^{-3}$.

highlight-line smoothness, the surface quality is much improved in the right-hand figures. We cannot find the difference from usual surface evaluation, especially in Fig. 3, but H is reduced to less than one half. In Fig. 4 and Fig. 5, highlight lines are better and the shapes of the evolute surfaces are quite different.

§5. Surface Modification by Specified Highlight Line

Next, we consider modification of a surface according to the designer's intention. A designer wants to specify a highlight line on the surface by indicating the line to be changed. We determine the control variables in (6) so that the surface has the specified highlight line. We calculate the squared sum of the angle difference between tangent directions of the two highlight lines at

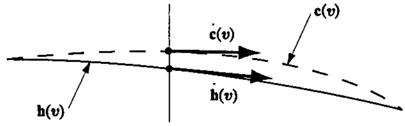
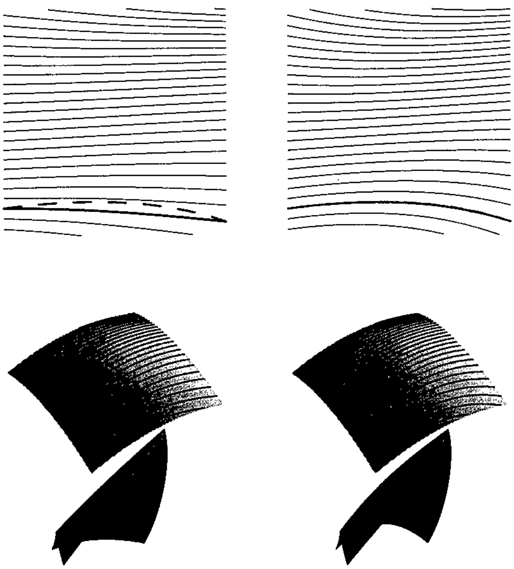


Fig. 6. Modification of surface by highlight line specification. A solid line $\mathbf{h}(v)$ is a highlight line to be modified and a dashed line $\mathbf{c}(v)$ is specified one.



(a) (b)

Fig. 7. Surface modification by highlight line specification.

the several corresponding points (see Fig. 6). Then, we change the surface to minimize the value of

$$E = \sum_{i=1}^{20} \arccos^2 \frac{\dot{\mathbf{c}}(v_i) \cdot \dot{\mathbf{h}}(v_i)}{|\dot{\mathbf{c}}(v_i)||\dot{\mathbf{h}}(v_i)|}. \tag{7}$$

Fig. 7 shows an example of surface modification. The upper two figures are projected highlight lines, and the lower two figures are an original surface and modified one with their evolute surfaces. In the left figure (a), a dashed line is a highlight line specified by a designer to change the corresponding highlight line (bold line). In the right figure (b), the surface is modified to have the specified highlight line. As a result, its silhouette pattern is changed, but the curvature distribution is smooth, as required by the designer.

§5. Summary

We have proposed generation and modification methods of surfaces which obtain not only smooth curvature distribution, but also smooth highlight lines. The generated surface is globally smooth because it is generated so that its evolute surface becomes smooth. Further, the shape of the evolute surface is determined to minimize the introduced highlight line criterion, while the surface satisfies the specified highlight line when it is given by a designer.

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